California Environmental Protection Agency

Air Resources Board

Detailed California-Modified GREET Pathway for California Average Electricity

Stationary Source Division

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The Staff of the Air Resources Board developed this preliminary draft version as part of the Low Carbon Fuel Standard Regulatory Process

The ARB acknowledges contributions from the California Energy Commission, TIAX, and Life Cycle Associates during the development of this document

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These comments will be compiled, reviewed, and posted to the LCFS website in a timely manner.

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SUMMARY

CA-GREET Model Pathway for California Average Electricity

A Well-To-Tank (WTT) Life Cycle Analysis of a fuel (or blending component of fuel) pathway includes all steps from feedstock production to final finished product. Tank-To-Wheel (TTW) analysis includes actual combustion of fuel (or use in a manner that generates power such as in electricity) for motive power. Together WTT and TTW analysis are combined together to provide a total Well-To-Wheel (WTW) analysis.

A Life Cycle Analysis Model called the **G**reenhouse gases, **R**egulated **E**missions, and **E**nergy use in **T**ransportation (GREET)[1] developed by Argonne National Laboratory has been used to calculate the energy use and GHG emissions generated during the entire process required to produce electricity. The model however, was modified by TIAX under contract to the California Energy Commission during the AB 1007 process[2]. Changes were restricted mostly to input factors (emission factors, generation mix, transportation distances, etc.) with no changes in methodology inherent in the original GREET model. The values, assumptions, and equations used in this document are from the CA-modified GREET model (greet1.7ca_v98.xls). This model is available for download from the Low Carbon Fuel Standard website at http://www.arb.ca.gov/fuels/lcfs/lcfs.htm.

The California-modified GREET model, herein referred to as "GREET", forms the basis of this document which details the energy use and GHG emissions for the generation and use of electricity as a transportation fuel. Figure 1 below shows the discrete components that form the electricity pathway. The original Argonne model uses a national average resource mix for electricity generation. The resource mix used here is however a California average electricity mix (resources are consistent with the mix of power consumed in California in 2005). Figure 2 provides the 2005 resource mix for California used in this document.

[1] http://www.transportation.anl.gov/software/GREET/
[2] http://www.energy.ca.gov/ab1007/

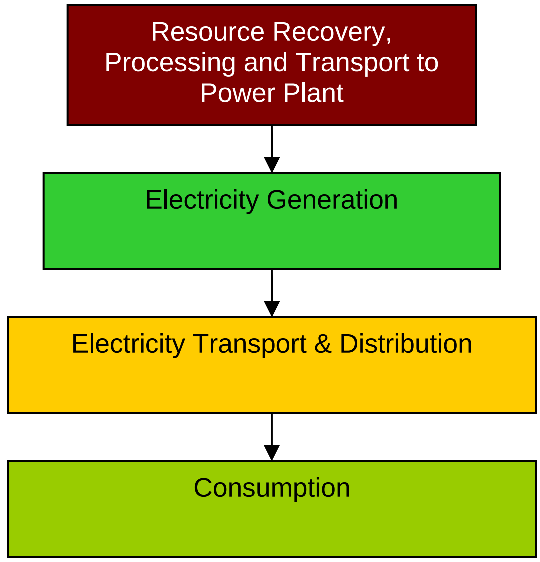

Figure 1. Discrete Components of the Electricity Pathway

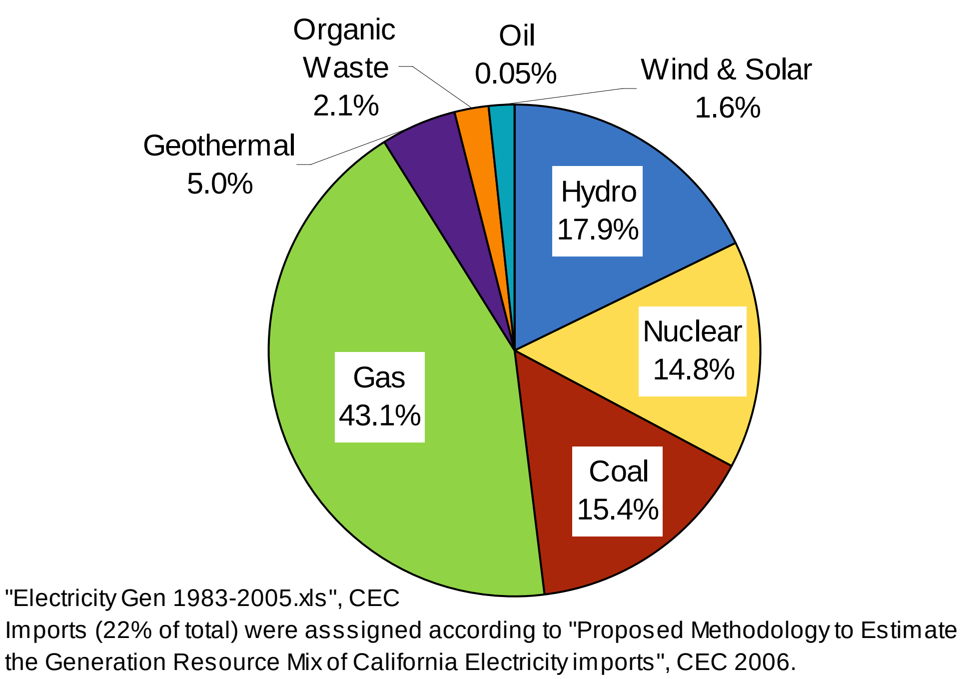

Figure 2. 2005 Resource Mix of Electricity Consumed in California

Several general descriptions and clarification of terminology used throughout this document are:

- GREET employs a recursive methodology to calculate energy consumption and emissions. To calculate WTT energy and emissions, the values being calculated are often utilized in the calculation. For example, crude oil is used as a process fuel to recover crude oil. The total crude oil recovery energy consumption includes the direct crude oil consumption AND the energy associated with crude recovery (which is the value being calculated).

- Btu/mmBtu is the energy input necessary in Btu to produce or transport one million Btu of a finished (or intermediate) product. This description is used consistently in GREET for all energy calculations. There are 1,055 MJ in one mmBtu of energy, so in order to convert one million Btu into MJ, divide the million Btu by 1055.

- gCO_2e/MJ provides the total greenhouse gas emissions on a CO_2 equivalent basis per unit of energy (MJ) for a given fuel. Methane (CH_4) and nitrous oxide (N_2O) are converted to a CO_2 equivalent basis using IPCC global warming potential values and included in the total.

- GREET assumes that VOC and CO are converted to CO_2 in the atmosphere and includes these pollutants in the total CO_2 value using ratios of the appropriate molecular weights.

- Process Efficiency for any step in GREET is defined as:

$$\text{Efficiency} = \text{energy output} / (\text{energy output} + \text{energy consumed})$$

Table A below provides a summary of the energy use and GHG emissions per MJ of electricity produced. Note that rounding of values has not been performed in several tables in this document. This is to allow stakeholders executing runs with the GREET model to compare actual output values from the CA-modified model with values in this document. The information in Table A is shown in Figure 3. From an energy perspective, energy in fuel (43.9%) and natural gas (32.4%) dominate the energy part of the WTW analysis and coal (48.4%) and natural gas (51.1%) related components dominate the GHG emissions for the electricity pathway. The values shown in this document are preliminary draft values and staff is in the process of evaluating them. Also, values reported within this document may be different from previously reported values (since electricity generation mix, process efficiency, and other factors may have been changed or updated). The areas that staff may revise include emission factors, energy intensity factors, % fuel shares, transport modes and their shares, etc. Expanded details are provided in Appendices A and B. A list of input values is provided in Appendix C.

Table A. Total Energy Consumption and GHG Emissions for CA Average Electricity Pathway

	Energy Required (Btu/mmBtu)	**Share of Total Energy Required (%)**	**GHG Emissions (gCO_2e/MJ)**	**Share of Total GHG Emissions (%)**
Residual oil	1,012	0.04%	0.2	0.1%
NG	739,040	32.4%	83.9	51.1%
Coal	272,751	12.0%	79.6	48.4%
Biomass	21,294	0.9%	0.2	0.1%
Nuclear	94,537	4.2%	0.5	0.3%
Other	150,039	6.6%	0	0
Total Well to Tank	1,278,673	56.1%	164.4	100.0%
Carbon /Energy in Fuel	1,000,000	43.9%	0.0	0.0%
Vehicle CH_4 and N_2O			0.0	0.0%
Total Well to Wheel	2,278,673	100%	164.4	100.0%

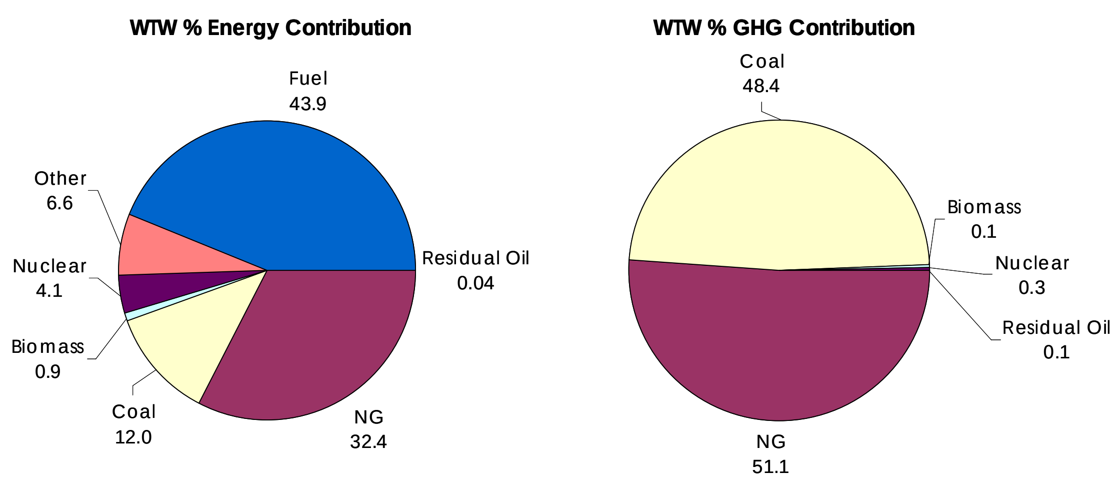

Figure 3. Percent Energy Contribution and Emissions Contribution from Well-to-Wheel (WTW)

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APPENDIX A

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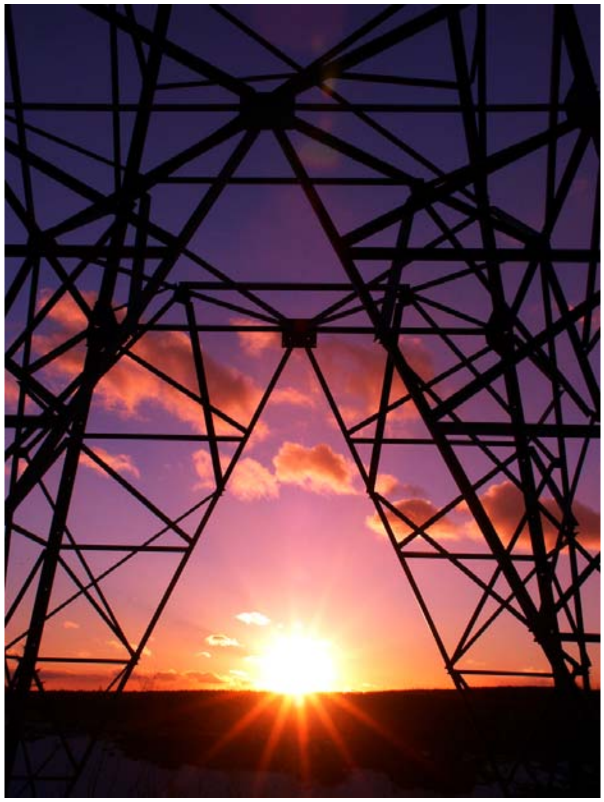
SECTION 1. DETAILS OF THE ELECTRICITY PATHWAY



1.1 Detailed Energy Consumption for the Electricity Pathway WTT

The first step in the electricity pathway is to determine direct fuel use at the electric power plants. Table 1.01 indicates how the different fuels are split by equipment type and the assumed unit efficiency (LHV basis) for each plant/fuel type combination. The weighted average efficiency for each fuel is shown in the last column. All power plant efficiencies shown are GREET defaults except slight adjustment to the natural gas combustion turbine efficiencies as follows:

- Simple Cycle Turbines: GREET default is 33.1% (LHV basis), the CA modified model uses 31.5%
- Combined Cycle Turbine: GREET default is 53% (LHV basis), the CA modified model uses 51.8%

Table 1.01 Power Plant Shares and Assumed Efficiencies for Each Power Plant Fuel Type

Process Fuel Type	**Power Plant Type**	**Plant Type Shares**	**Plant Efficiency (LHV)**	**Average Efficiency for Fuel (LHV)**
Residual Oil	Boiler	100%	34.8%	34.8%
Natural Gas	Boiler	20%	34.8%	38.9%
	Simple Cycle Turbine	36%	31.5%	
	Combined Cycle Turbine	44%	51.8%	
Coal	Boiler	100%	34.1%	34.1%
Biomass	Boiler	100%	32.1%	32.1%
Nuclear			100%	100%
Other			100%	100%

The intent of the California Average case is to reflect the resource mix of electricity consumed in California. Table 1.02 illustrates how GREET directly utilizes these splits (shown in Fig. 2), the average power plant efficiency, and the transmission & distribution loss factor to calculate direct power plant fuel consumption. Note that 1,000,000 Btu/mmBtu electricity of the fuel consumed becomes electricity, so this is subtracted from the total direct energy use to arrive at a net direct energy use.

Table 1.02 Calculation of Direct Energy Consumption (Btu/mmBtu) to Produce Electricity

Process Fuel Type	MWh Shares	Avg Eff (LHV)	Calculation of Direct Energy Use per MJ Composite Electricity Produced	Direct Energy Use, Btu/mmBtu
Residual Oil	0.05%	34.8%	10^6 Btu/mmBtu/ (0.348) / (1-.081) * 0.0005	1,563
Natural Gas	43.1%	38.9%	10^6 Btu/mmBtu/ (0.389) / (1-.081) * 0.431	1,204,871
Coal	15.4%	34.1%	10^6 Btu/mmBtu/ (0.341) / (1-.081) * 0.154	490,460
Biomass	1.1%	32.1%	10^6 Btu/mmBtu/ (0.321) / (1-.081) * 0.011	37,288
Nuclear	14.8%	100%	10^6 Btu/mmBtu/ (1) / (1-.081) * 0.148	161,262
Other	25.5%	100%	10^6 Btu/mmBtu/ (1) / (1-.081) * 0.255	277,911
TOTAL DIRECT ENERGY USE				**2,173,356**
NET DIRECT ENERGY USE (less 1 mmBtu electricity produced)				**1,173,356**

Note: Other = hydro, wind, solar, geothermal and assumed Transmission Loss is 8.1%

The values provided in Table 1.02 are direct energy consumption per Btu of electricity produced. This is not the total energy required however, since GREET also accounts for the "upstream" energy associated with each of the fuels utilized. For example, 1,563 Btu of residual oil are utilized to produce electricity. The total energy associated with the 1,563 Btu of residual oil includes the energy to recover the crude and refine it to residual oil. Table 1.03 demonstrates how the direct energy consumption values shown in Table 1.02 are utilized to calculate total energy required to produce electricity. Actual values used in the formulae are shown in Table 1.04.

From Tables 1.02 and 1.03, the total energy to produce 1 mmBtu of electricity at the wall outlet is the sum of direct energy and upstream energy: Total Energy = 1,173,355 Btu/mmBtu + 105,317 Btu/mmBtu = 1,278,672 Btu/mmBtu.

Table 1.03 Calculation of Upstream Energy Consumption from Direct Energy Consumption

Fuel Type	Formula	Btu/mmBtu
Residual Oil	$A * (B*C + D)/ 10^6$	168
Natural Gas	$E * F / 10^6$	88,552
Coal	$G * H / 10^6$	7,960
Biomass	I * (J) / K	1,162
Nuclear	L * M / N /1000/3412	7,474
Total		**105,317**

Note: There are 1,000 kWh/MWh and 3,412 Btu/kWh.

Table 1.04 Values used in Table 1.03 above

Factor	Value	Description	Source
A	1,563	Btu of direct residual oil used per mmBtu electricity produced.	GREET calculation
B	33,220	Btu required to recover 1 mmBtu crude for US refineries.	GREET calculation
C	1.0000	Loss factor for residual oil.	GREET default
D	74,237	Btus are required to refine and transport 1 mmBtu residual oil.	GREET calculation
E	1,204,871	Btu of direct NG used per mmBtu electricity produced.	GREET calculation
F	73,495	The energy to recover, process and transport 1 mmBtu North American NG	GREET calculation
G	490,460	Btu of direct coal use to produce 1 mmBtu electricity.	GREET calculation
H	16,230	The energy to mine, clean and transport coal to the power plant	GREET calculation
I	37,288	Btu of direct biomass use per mmBtu electricity produced.	GREET calculation
J	524,057	Energy associated with tree farming, fertilizer application, pesticide application and tree transport in Btu/ton trees	GREET default
K	16,811,000	LHV of trees is 16,811,000 Btu/ton trees.	GREET default
L	161,262	Btu of nuclear energy used per mmBtu electricity produced.	GREET calculation
M	1,095,281	To produce 1 g of U-235, this many Btu are required.	GREET calculation
N	6.926	MWh of electricity produced per g U-235.	GREET default

1.2 Detailed GHG Emissions for the Electricity Pathway WTT

The GHG emissions for this pathway consist of the emissions associated with generating electricity and the upstream emissions associated with producing and transporting each fuel to the power plant. The specific emission factors utilized here are presented in Table 1.05. All emission factors utilized are GREET defaults with the following exceptions:

- Coal fired Utility Boiler N_2O – default value is 1.06. Value utilized is 0.57[3]
- Biomass Utility Boiler N_2O – default value is 11. Value utilized is 6.21 from AP-42.
- Biomass Utility Boiler CH_4: Default value is 3.83. Value utilized is 10.03 from AP-42
- NG Utility Boiler N_2O: Default value is 1.10. Value utilized is 0.36 from AP-42

Table 1.05 Emission Factors for Electricity Generation, g/MMBtu (LHV)

	Residual Oil	**Natural Gas**	**Natural Gas**	**Natural Gas**	**Coal**	**Biomass**
	Utility Boiler	Utility Boiler	Simple Cycle Turbine	Combined Cycle Turbine	Utility Boiler	Utility Boiler
VOC	2.023	1.557	1.000	3.429	1.140	5.341
CO	15.764	16.419	24.000	24.000	100.000	76.800
CH_4	0.910	1.100	4.260	4.260	1.200	10.030
N_2O	0.360	0.315	1.500	1.500	0.570	6.210
CO_2	85,048	58,198	58,179	58,171	137,356	102,224

These emission factors are subsequently converted to an output basis (g/kWh) as follows:

$$\text{Emission factor g/kWh} = \text{g/MMBtu / efficiency / } 10^6 \text{ Btu/MMBtu} * 3412 \text{ Btu/kWh}$$

Table 1.06 provides the output based emission factors by fuel type; for natural gas, the weighted average emission factor for each of the combustion device types is shown.

[3] IPCC Vol 3, Table 1-15. Agrees with Climate Action Registry and AP-42.

Table 1.06 Emission Factors for Electricity Generation, Average for Fuel Type, g/kWh (LHV)

	Residual Oil	Natural Gas	Coal	Biomass
	Utility Boiler	Weighted Avg of Boiler, SCCT, CCCT	Utility Boiler	Utility Boiler
VOC	0.0198	0.0169	0.0114	0.0568
CO	0.1546	0.1954	1.0006	0.8163
CH_4	0.0198	0.0169	0.0114	0.0568
N_2O	0.1546	0.1954	1.0006	0.8163
CO_2	834	510	1,374	1,087

The last step is to multiply the output based emission factors by the specified fuel share and then divide by (100-8.1) to account for the 8.1% transmission loss (default). These values are subsequently multiplied by 1,000,000 and divided by 3,412 to convert back to g/MMBtu at the wall outlet. The final direct emissions are provided in Table 1.07. There are no direct emissions for nuclear power or the "other" non-combustible power categories.

Table 1.07. Direct Emissions for Electricity Production, g/mmBtu at Wall Outlet

	VOC	CO	CH_4	N_2O	CO_2	GHG	GHG gCO_2e/MJ
Residual Oil	0.003	0.025	0.003	0.025	132	140	0.13
Natural Gas	2.324	26.873	2.324	26.873	70,100	78,157	74.08
Coal	0.559	49.046	0.559	49.046	67,367	81,976	77.70
Biomass	0.199	2.864	0.374	0.232	0	82	0.08
Total	**3.09**	**78.81**	**3.260**	**76.18**	**137,601**	**160,356**	**152**

The emissions associated with recovering, processing, and transporting the electricity generating fuels to the power plants are the "upstream" emissions. These are calculated from the direct energy consumption values shown in Table 1.02. Table 1.08 illustrates the upstream calculations for CO_2 with Table 1.09 providing the values for entries in Table 1.08. Table 1.10 provides the upstream emissions for each pollutant and fuel type.

Table 1.08 Calculation of Upstream CO_2 Emissions from Direct Energy Consumption

Fuel Type	Formula	gCO_2/mmBtu
Residual Oil	$A^* (B+ C)/ 10^6$	12
Natural gas	$D * E /10^6$	6,427
Coal	$F * G / 10^6$	615
Biomass	H * I / J	86
Nuclear	K * L / M / 1000 / 3412	480
Total		**7,621**

Table 1.09 Values used in Table 1.08

Factor	Value	Description	Source
A	1,563	Btu of direct residual oil used per mmBtu electricity produced	GREET calculation
B	3,134	The crude recovery and transport CO_2 emissions in g/mmBtu	GREET calculation
C	5,105	The CO_2 emissions from producing and transporting residual oil in g/mmBtu	GREET calculation
D	1,204,871	Btu of direct NG fuel used per mmBtu electricity produced	GREET calculation
E	5,335	Total CO_2 emissions to recover, process and transport NG is g/mmBtu	GREET calculation
F	490,460	Btu of direct coal used per mmBtu electricity produced	GREET calculation
G	1,253	Total CO_2 emissions to recover, clean and transport coal in g/mmBtu.	GREET calculation
H	37,288	Btus of direct biomass use per mmBtu electricity produced.	GREET calculation
I	38,880	Total CO_2 emissions associated with tree farming, fertilizer application, pesticide application and tree transport in /ton trees.	GREET calculation
J	16,811,000	LHV of trees in Btu/ton trees	GREET default
K	161,262	Btu of nuclear energy used per mmBtu electricity produced.	GREET calculation
L	70,340	gCO_2 emitted per g U-235 produced	GREET calculation
M	6.926	MWh of electricity produced per g U-235	GREET default

Table 1.10 Upstream Emissions for Electricity Production, g/mmBtu at Wall Outlet (by fuel)

	VOC	CO	CH_4	N_2O	CO_2	GHG	GHG gCO_2e /MJ
Residual Oil	0.01	0.02	0.15	0.002	12.93	17	0.02
Natural Gas	7.91	14.39	167.69	0.235	6427.46	10,401	9.86
Coal	3.77	1.51	58.56	0.069	614.57	1,996	1.896
Biomass	0.08	0.28	0.10	0.044	86.24	102	0.10
Nuclear	0.24	1.66	0.92	0.211	480.00	567	0.54
Total	**12**	**17.9**	**227.42**	**0.6**	**7621.2**	**13,083**	**12.4**

Finally, Table 1.11 combines the direct and upstream emissions, converts CO and VOC to CO_2, and calculates total GHG emissions for this pathway.

Table 1.11 Total GHG Emissions for Electricity Production, g/mmBtu at Wall Outlet (by fuel)

	VOC	CO	CH_4	N_2O	CO_2	GHG	GHG gCO_2e/MJ
Residual Oil	0.013	0.048	0.153	0.027	146	158	0.149
Natural Gas	10.232	41.265	170.009	27.108	76,528	88,558	83.942
Coal	4.333	50.554	59.123	49.115	67,982	83,973	79.595
Biomass	0.283	3.143	0.477	0.276	86	185	0.175
Nuclear	0.239	1.665	0.916	0.211	480	567	0.537
Total	**15.1**	**96.68**	**230.68**	**76.74**	**145,222**	**173,440**	**164.40**

1.3 TTW Portion from Vehicle

For electric vehicles, the tailpipe emissions are zero, so the entire fuel cycle emissions would be:

Total Fuel Cycle = WTT + Vehicle = 164.4 + 0 = 164.4 gCO_2e/MJ

Note: On a per mile basis, the AB1007 fuel consumption is 1.12 MJ/mi (4.6/4.1) for an electric vehicle. The resulting emissions are:

Total Fuel Cycle = 164.4 gCO_2e/MJ * 1.12 MJ/mi = 184.13 gCO_2e/mi

APPENDIX B

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SECTION 2. DETAILS OF ENERGY USE AND GHG EMISSIONS FROM RECOVERY, PROCESSING AND TRANSPORT OF FEEDSTOCKS FOR ELECTRICITY GENERATION

The California Average Electricity pathway utilizes five feedstocks for electricity production: **residual oil, natural gas, coal, biomass and uranium**. The upstream energy and emissions for recovery, processing and transport of each of these feedstocks was noted in the preceding sections. The total upstream contribution to WTT energy and emissions is approximately 8 percent. The majority of the upstream emissions are attributable to natural gas and coal recovery, processing and transport. Figure 4 indicates the contribution of each upstream component to total GHG emissions.

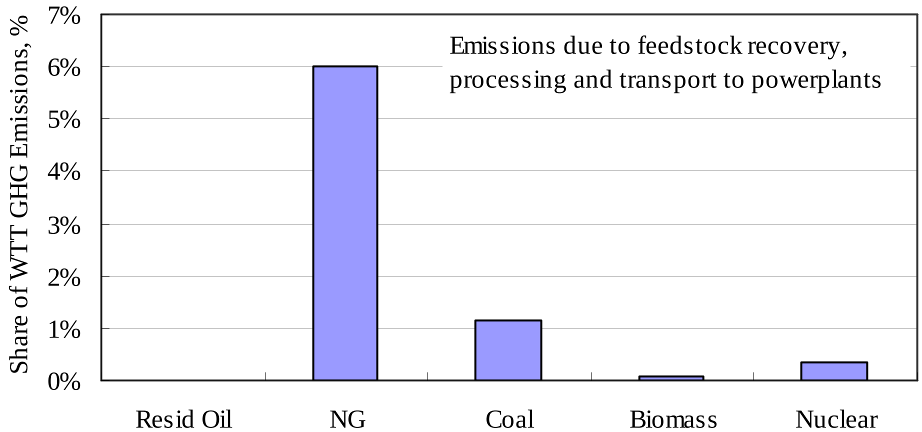

Figure 4. Contribution of Recovery, Processing and Transport of Electricity Feedstocks to Total Electricity Pathway GHGs

Detailed descriptions and quantification of several of these feedstocks may be found in other pathway documents:

- Residual oil is described in the CARBOB pathway
- Natural gas is described in the CNG pathway
- Biomass is similar to the corn farming methodology presented in the ethanol pathway and the soybean farming methodology presented in the biodiesel pathway

The natural gas values are nearly identical – very small differences may be seen due to the pathway electricity mix. The electricity pathway utilizes the California average electricity mix while the CNG pathway assumes a marginal mix (natural gas combined cycle combustion turbines and renewables). Because the values are so close, we refer the reader to the CNG pathway document for this feedstock.

The residual oil recovery, refining and transport energy and emission quantification methodology is documented in the CARBOB pathway. However, for the CARBOB pathway the California average crude recovery efficiency (94%) is utilized and in the electricity pathway, the GREET default recovery efficiency is assumed (98%), along with default transportation modes and distances. The resulting values are fairly different, so we provide the detailed residual oil calculations below.

The biomass feedstock for electricity production is the GREET default, farmed trees. The energy and emission quantification methodology is the same as for corn farming (ethanol pathway) and soybean (biodiesel pathway) farming, but the values are different, so a detailed description of the biomass farming and transport emissions is provided. This document does not provide detailed descriptions of the farm chemical (fertilizers, herbicides, pesticides) production and transportation energy and emission calculations. Values are shown for farm chemicals and the reader is referred to the ethanol pathway for a detailed description of the underlying assumptions. The remaining feedstocks, coal and uranium, are not described in any of the other pathway descriptions and are therefore provided below.

Table 2.01 provides the upstream energy and CO_2 values utilized in the electricity pathway. The following sections will provide the detailed calculations that result in these values.

Table 2.01 Upstream Energy and CO_2 Emissions for Electricity Production

	Upstream Energy Btu/mmBtu		**Upstream gCO_2/mmBtu**	
Residual Oil: Crude Recovery and Transport	33,220	"B" in Tables 1.03 and 1.04	3,134	"B" in Tables 1.08 and 1.09
Residual Oil: Refining and Transport	74,237	"D" in Tables 1.03 and 1.04	5,105	"C" in Tables 1.08 and 1.09
Natural Gas	73,495	"F" in Tables 1.03 and 1.04	5,335	"E" in Tables 1.08 and 1.09
Coal	16,230	"H" in Tables 1.03 and 1.04	1,253	"G" in Tables 1.08 and 1.09
Biomass	524,057	"J" in Tables 1.03 and 1.04	38,880 g/ton	"I" in Tables 1.08 and 1.09
Nuclear	1,095,281	"M" in Tables 1.03 and 1.04	70,340 g/g U-235	"L" in Tables 1.08 and 1.09

2.1 Residual Oil

The pathway steps for residual oil production include crude recovery, crude transport, refining and residual oil transportation (Table 2.02). In this section, we establish the values of 33,220 Btu/mmBtu for crude recovery and transport and 74,237 Btu/mmBtu for refining and transport of residual oil Shown in Table 2.01. Note that crude recovery energy includes crude transport and refining energy includes residual oil transport. We also establish the CO_2 values of 3,134 g/mmBtu for crude recovery and transport and 5,105 g/mmBtu for refining and residual oil transport.

Table 2.02 Summary of the Feedstock Residual Oil Energy and Emissions

	Energy Use Btu/mmBtu	**GHG Emissions gCO_2e/MJ**
Crude Recovery	26,947	3.089
Crude Transport	6,272	0.471
Crude Oil Total	**33,220**	**3.560**
Residual Oil Refining	66,767	4.674
Residual Oil Transport	7,470	0.600
Refining & Transport Total	**74,237**	**5.274**
Residual Oil Total	**107,455**	**8.834**

2.11 Crude Oil Recovery

Crude Oil Recovery Energy Consumption

For this pathway, the crude oil recovery efficiency is the GREET default 98%. Note that this is significantly higher than the estimated California average value which includes TEOR crude. Table 2.03 indicates how direct energy consumption for each fuel type is calculated based on the assumed crude recovery efficiency.

Table 2.03 Calculation of Direct Energy Consumption for Crude Recovery from Process Efficiency

Fuel Type	Fuel Shares	Relationship of Recovery Efficiency (0.98) and Fuel Shares	Btu/mmBtu
Crude oil	1.0%	$(10^6)(1/0.98 – 1)(0.01) = 204$	204
Residual oil	1.0%	$(10^6)(1/0.\ 98 – 1)\ (0.01) = 204$	204
Diesel fuel	15.0%	$(10^6)(1/0.\ 98 – 1)\ (0.15) = 3057$	3,057
Gasoline	2.0%	$(10^6)(1/0.\ 98 – 1)(0.02) = 408$	408
Natural gas	62.0%	$(10^6)(1/0.\ 98 – 1)(0.62) = 12{,}635$	12,635
Electricity	19.0%	$(10^6)(1/0.\ 98 – 1)(0.19) = 3{,}872$	3,872
Feed Loss	0.14%	$(10^6)(1/0.\ 98 – 1)(0.0014) = 28$	28
Total Direct Energy Consumption in Crude Recovery			**20,408**

The values in Table 2.03 reflect direct energy consumption to recover crude oil. In addition to direct fuel consumption, we must account for the energy utilized to produce these fuels, the “upstream” energy. Table 2.04 indicates how the direct energy consumption values are utilized to determine total (direct + upstream) energy for crude recovery. Table 2.05 provides values and descriptions for the formulas used in Table 2.04.

Table 2.04 Adjustment to Crude Recovery Energy to Account for Upstream Energy Inputs

Fuel Type	Formula	Btu/mmBtu
Crude oil	$204\ (1 + A/10^6)$	209
Residual oil	$204\ (1 + (B*D+ C)/\ 10^6)$	226
Diesel fuel	$3057\ (1 + (B*F + E)/\ 10^6)$	3,598
Gasoline	$408\ (1 + (B*H + G)/\ 10^6)$	496
Natural gas	$12{,}635\ (1 + I/10^6)$	13,564
Electricity	$3{,}872\ (K+ J)/\ 10^6$	8,823
Feed Loss	28	28
Total WTT energy for crude recovery		26,946
Total WTT energy with loss factor applied		**26,947**

Note:* Loss factor 1.000062 applied to total crude recovery energy.

Table 2.05 Details for Formulas in Table 2.04

Quantity	Description
A = 26,946	WTT energy (Btu/mmBtu crude) to recover crude oil. This value calculated as the total WTT energy for crude recovery in Table 1.02 above. It is also an input the total WTT energy calculation This is one instance of a “recursive” calculation in GREET.
B = 33,220	WTT energy (Btu/mmBtu crude oil) required to recover and transport crude to US refineries.
C = 74,237	WTT energy (Btu/mmBtu residual oil) required to refine crude oil to residual oil and to transport residual oil to location where it is used.
D = 1.0000	Loss factor for Residual Oil which is a GREET default value.
E = 143,899	WTT energy (Btu/mmBtu diesel) required to refine crude oil to diesel and transport diesel.
F = 1.00002	Loss factor for diesel fuel which is default GREET value.
G = 184,474	WTT energy (Btu/mmBtu gasoline) to produce and transport conventional gasoline.
H = 1.00019	Loss factor for gasoline which is default GREET value.
I = 73,495	WTT energy (Btu/mmBtu Natural gas) to recover, process and transport natural gas as stationary fuel. This is a GREET calculated value.
J = 2,173,356	Total energy required (Btu/mmBtu electricity) to produce and transport electricity.
K = 105,317	Total energy required (Btu/mmBtu electricity produced) to recover, process and transport all feedstocks utilized in electricity production for this pathway.

Crude Oil Recovery Emissions

Similar to the energy calculations, the GHG emissions associated with crude recovery consist of both direct and upstream emissions. The direct emissions are simply the direct fuel consumption multiplied by the appropriate emission factor. The upstream emissions are the total emissions associated with recovery, production and transport of the fuel being consumed. For direct emissions, the fuel is split among different combustion devices, each with their own emission factors. Table 2.06 provides the assumed split of combustion devices for direct fuel combustion. For details of the emission factors utilized for each fuel/equipment combination, please refer to the CNG pathway document.

Table 2.06 Shares of Equipment for Crude Recovery Direct Energy Consumption

	Boiler	**Engine**	**Turbine**
Crude Oil	100%		
Residual Oil	100%		
Diesel	25%	50%	25%
Gasoline		100%	
Natural Gas	50%	50%	

The direct emissions resulting from direct fuel consumption are provided in Table 2.07. The upstream emissions associated with recovery, processing and transport of these process fuels are provided in Table 2.08. Please refer to the CARBOB pathway document for the calculation method. Total crude recovery emissions are provided in Table 2.09 (the sum of direct and upstream).

Table 2.07 Direct Emissions for Crude Recovery, g/mmBtu

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**	**GHG**	**GHG g/MJ**
Crude	0.000	0.005	0.000	0.000	15.746	15.877	0.015
Residual Oil	0.000	0.003	0.000	0.000	17.333	17.367	0.016
Diesel	0.129	0.573	0.013	0.005	237.713	240.755	0.228
Gasoline	0.724	5.331	0.040	0.001	20.575	32.419	0.031
Natural Gas	0.317	2.782	3.161	0.030	1700.014	1786.941	1.694
Electricity	0	0	0	0	0	0.000	0.000
Non-Combustion	0.702		14.094			326.361	0.309
Total	**1.873**	**8.694**	**17.309**	**0.036**	**1,991**	**2,420**	**2.294**

Table 2.08 Upstream Emissions for Crude Recovery, g/mmBtu

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**	**GHG**	**GHG g/MJ**
Crude	0.000	0.002	0.001	0.000	0.544	0.598	0.001
Residual Oil	0.001	0.003	0.020	0.000	1.685	2.235	0.002
Diesel	0.023	0.050	0.307	0.003	38.953	46.956	0.045
Gasoline	0.005	0.008	0.042	0.000	6.940	8.054	0.008
Natural Gas	0.083	0.151	1.759	0.002	67.405	109.076	0.103
Electricity	0.058	0.374	0.893	0.297	563.091	672.358	0.637
Non-Combustion	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	**0.171**	**0.587**	**3.021**	**0.303**	**678.618**	**839.276**	**0.796**

Table 2.09 Total Emissions for Crude Recovery, g/mmBtu

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**	**GHG**	**GHG gCO_2e/MJ**
Crude	0.000	0.007	0.001	0.000	16.290	16.474	0.016
Residual Oil	0.002	0.006	0.020	0.000	19.018	19.602	0.019
Diesel	0.152	0.623	0.320	0.008	276.666	287.711	0.273
Gasoline	0.729	5.339	0.082	0.001	27.515	40.473	0.038
Natural Gas	0.400	2.933	4.920	0.032	1767.418	1896.017	1.797
Electricity	0.058	0.374	0.893	0.297	563.091	672.358	0.637
Non-Combustion	0.702	0.000	14.094	0.000	0.000	326.361	0.309
Total	**2.044**	**9.282**	**20.330**	**0.339**	**2669.999**	**3258.996**	**3.089**

2.12 Crude Transport

The values presented in this section are the energy consumed and emissions produced in transporting the crude oil to U.S. refineries. For transport to U.S. refineries, GREET assumes 5 miles of barge travel and 750 miles of pipeline travel. All values utilized here are GREET defaults.

Crude Transport Energy Consumption

Details of how energy use is calculated for both types of modes of transport are provided in Table 2.10 below with values used in the calculation provided in Table 2.11. Both modes utilize common factors such as lower heating values (LHV) and density of crude, and transport mode specific factors such as energy consumed per mile of transport to calculate energy use for specific distances transported.

Table 2.10 Details of Energy Consumed for Crude Transport

	Detailed Calculations	Btu/mmBtu
Feed Loss	(Loss Factor – 1)*10^6	62
Barge	(Density of crude/LHV of crude)*(Energy consumed)*(miles traveled)*(1/454)*(1/2000)*(1+WTT of Residual Oil)*10^6	107
Pipeline	(Density of crude/LHV of crude)*(Energy consumed)*(miles traveled)*(1/454)*(1/2000)*(24%*WTT NG + 20%* WTT Diesel + 50%*WTT Residual + 6%*WTT Electric)*10^6	6,103
Total Energy Consumed for Crude Transport		**6,272**

Table 2.11 Values for Formulas in Table 2.10

Description	Value	Source
Loss Factor of Crude T&D	1.000062	GREET calculation
Miles traveled by Barge (miles)	5	AB 1007 value
Pipeline transport (miles)	750	AB 1007 value
Density of crude (grams/gallon)	3,205	GREET default
Lower heating value (LHV) of crude (Btu/gallon)	129,670	GREET default
Energy consumed by Barge (Btu/ton-mile)	710	GREET default
Energy consumed by Pipeline (Btu/ton-mile)	253	GREET default
Conversion from pounds to grams	454	
Conversion from tons to pounds	2,000	
WTT Energy Factor for Residual Oil, Btu/Btu	0.107	GREET calculation
WTT Energy Factor for Electricity, Btu/Btu	2.279	GREET calculation
WTT Energy Factor for Diesel, Btu/Btu	0.177	GREET calculation
WTT Energy Factor for Natural Gas, Btu/Btu	0.073	GREET calculation

Note that the total crude recovery and transport energy is 6,272 + 26,947 = 33,220 Btu/mmBtu. This is the total energy associated with crude recovery and transport as shown in the Table above, and is used to calculate the upstream energy associated with residual oil use for electricity consumption.

Crude Transport GHG Emissions

Table 2.12 details CO_2 emissions related to crude transport and distribution. These calculations assume 5 miles by barge and 750 miles by pipeline, as detailed in the Energy Use for Crude Transport section above. Table 2.13 provides values for various terms used in Table 2.12. Total GHG emissions are provided in Table 2.14.

Table 2.12 Crude Transport CO_2 Emissions

Mode	Formula	gCO_2/mmBtu	gCO_2/MJ
Barge	(Density of crude/LHV of crude)*(miles traveled) *(1/454)*(1/2000)*((Energy intensity on trip from origin to destination*(emission factor for boiler residual oil + WTT CO_2 for residual oil)) + (Energy intensity on return trip*(emission factor for boiler residual oil + WTT CO_2 for residual oil))	9	0.01
Pipeline	(Density of crude/LHV of crude)*(Energy intensity of pipeline)*(miles traveled)*(1/454)*(1/2000) * (turbine share * (% NG * (NG turbine emission factor + NG WTT) + % electricity * WTT electricity + % diesel * (diesel turbine emission factor + WTT diesel) + % residual oil * (resid oil turbine emission factor + WTT resid oil) + current engine share *(% NG * (NG engine emission factor + NG WTT) + % electricity * WTT electricity + % diesel * (diesel engine emission factor + WTT diesel) + % residual oil * (resid oil engine emission factor + WTT resid oil) + future engine share * (% NG * (NG future engine emission factor + NG WTT) + % electricity * WTT electricity + % diesel * (diesel future engine emission factor + WTT diesel) + % residual oil * (resid oil future engine emission factor + WTT resid oil))	456	0.43
Total		**465**	**0.44**

Table 2.13 Values of Properties Used in Table 2.04

Parameters	**Values**	**Source**
Miles traveled by Barge, miles	5	AB 1007 value
Pipeline transport distance, miles	750	AB 1007 value
Density of crude, g/gallon	3,205	GREET default
Lower heating value (LHV) of crude, Btu/gallon	129,670	GREET default
Energy intensity of Barge on trip to destination, Btu/ton-mile	403	GREET default
Energy intensity of Ocean Tanker on return trip, Btu/ton-mile	307	GREET default
Energy intensity of Pipeline, Btu/ton-mile	253	GREET default
Conversion from pounds to grams	454	
Conversion from tons to pounds	2,000	
Conversion from MJ to mmBtu	1,055	
CO_2 Emission factor for Residual Oil Boiler, g/mmBtu	84,048	GREET default
CO_2 Emission factor for Residual Oil Turbine, g/mmBtu	85,061	GREET default
CO_2 Emission factor for Residual Oil current engine, g/mmBtu	84,219	GREET default
CO_2 Emission factor for Residual Oil future engine, g/mmBtu	84,219	GREET default
CO_2 Emission factor for Diesel Turbine, g/mmBtu	78,179	GREET default
CO_2 Emission factor for Diesel current engine, g/mmBtu	77,337	GREET default
CO_2 Emission factor for Diesel future engine, g/mmBtu	77,337	GREET default
CO_2 Emission factor for Natural Gas Turbine, g/mmBtu	58,179	GREET default
CO_2 Emission factor for Natural Gas current engine, g/mmBtu	56,013	GREET default
CO_2 Emission factor for Natural Gas future engine, g/mmBtu	56,551	GREET default
WTT Emissions for Residual Oil, Btu/Btu	8,268	GREET Calculation
WTT Emissions for Diesel, Btu/Btu	12,743	GREET Calculation
WTT Emissions for Natural Gas, Btu/Btu	5,335	GREET Calculation
WTT Emissions for Electricity	145,421	GREET Calculation

Table 2.14 Total GHG Emissions Crude Transport and Distribution

GHG	(g/mmBtu)	Formula to convert to CO_2e	GHG $gCO_2e/mmBtu$	GHG gCO_2e/MJ
CO_2	465	465*1	465	0.44
CH_4	0.80	0.80*23	18.48	0.02
N_2O	0.038	0.038*296	11.38	0.01
CO	1.10	1.10*0.43*(44/12)	1.72	0.00
VOC	0.22	0.22*0.85*(44/12)	0.68	0.00
Total GHG emissions			**497**	**0.47**

Note that total CO_2 emissions for crude recovery and transport are 465 + 2670 = 3,135 g/mmBtu of crude oil. This is the value indicated in Table 2.01 of the main document to calculate the electricity pathway upstream emissions.

2.13 Crude Refining to Residual Oil

Crude Refining Energy Consumption

Like other pathway stages, the stage that refines crude into residual oil is defined by assumed process efficiency and fuel shares. Table 2.15 provides the residual oil refining process efficiency, fuel shares and resulting direct fuel consumption for refining. The assumptions for refining efficiency and fuel shares are GREET defaults.

Table 2.15 Calculating Direct Energy Consumption for Crude Refining to Residual Oil

Fuel Type	Fuel Shares	Calculating Direct Fuel Consumption from Efficiency (0.955) and Fuel Shares	Direct Fuel Consumption Btu/mmBtu Residual Oil
Residual Oil	6%	(1,000,000)(1/0.955 – 1)(0.06)	2,827
Natural Gas	14%	(1,000,000)(1/0.955 – 1) (0.14)	6,597
Electricity	30%	(1,000,000)(1/0.955 – 1)(0.30)	14,136
Refinery Still Gas	50%	(1,000,000)(1/0.955 – 1)(0.50)	23,560
Total Direct Energy Consumption for Residual Oil Refining			**47,120**

The values in Table 2.15 only represent the direct fuel consumption. We need to account for the energy consumed to recovery and produce these process fuels, the upstream energy. Table 2.16 illustrates the equations used to determine total fuel consumption for crude refining to residual oil. Table 2.17 details the values and descriptions for the formulas presented in Table 2.16.

Table 2.16 Calculation of Total Fuel Consumption from Direct Fuel Consumption

Fuel Type	Formula	Btu/mmBtu
Residual Oil	$2,827*(1 + (A*B+C)/10^6)$	3,131
Natural Gas	$6,597*(1 + D/ 10^6)$	7,082
Electricity	$14,136*((E+F)/ 10^6)$	32,212
Refinery still gas	$23,560*(1 + (A/ 10^6))$	24,343
Total (direct + upstream) energy for residual oil refining		**66,767**

Table 2.17 Details for Formulas in Table 2.16

Quantity	Description
A = 33,220	Energy required to produce and transport crude as feedstock for use in US refineries, a GREET calculated value.
B = 1.000	Loss factor, a GREET default.
C = 74,237	Energy (Btu/mmBtu of residual oil) to refine and transport residual oil, a GREET calculated value.
D = 73,495	Energy (Btu/mmBtu of natural gas) required to recover, process and transport natural gas as a stationary fuel, a GREET calculated value.
E = 105,317	Total energy (Btu/mmBtu of electricity) required to recover, process and transport all feedstocks used to generation eletctricity, a GREET calculated value.
F = 2,173,356	Energy required in Btu to produce one million Btu of electricity, a GREET calculated value.

Crude Refining GHG Emissions

Like the energy, emissions associated with refining may be divided into direct emissions and upstream emissions. The direct emissions are the direct fuel used in refining multiplied by the appropriate emission factor. The upstream emissions are the emissions associated with recovery, processing and transport of the fuels directly used in refining. To calculate the direct emissions, first the direct fuel use is split by equipment shares. Table 2.18 provides the GREET default equipment shares for fuels used to refine residual oil.

Table 2.18 Shares of Equipment for Residual Oil Refining Direct Energy Consumption

	Direct Fuel Use Btu/mmBtu	Large Boiler	Small Boiler	Turbine
Residual Oil	2,827	100%		
Natural Gas	6,597	60%	15%	25%
Refinery Gas	23,560	60%	15%	25%

Table 2.19 provides the direct GHG emissions (note that VOC and CO are assumed to convert to CO_2 and are included in the GHG totals. Table 2.20 provides the calculation methodology for determining upstream CO_2 emissions from direct fuel consumption. Table 2.20 provides upstream emissions for each greenhouse gas constituent and finally Table 2.21 provides total (direct + upstream) emissions for residual oil refining.

Table 2.19 Direct GHG Emissions from Residual Oil Refining, g/mmBtu

	VOC	CO	CH_4	N_2O	CO_2	CO_2*	GHG	GHG gCO_2e/MJ
Residual Oil	0.003	0.045	0.009	0.001	240.441	240.519	241.031	0.228
Natural Gas	0.010	0.133	0.012	0.004	383.869	384.110	385.590	0.365
Electricity	0	0	0	0	0	0	0	0
Refinery Gas	0.036	0.475	0.045	0.014	1370.961	1371.821	1377.108	1.305
Total	**0.049**	**0.653**	**0.066**	**0.019**	**1995.271**	**1996.**450	**2003.729**	**1.899**

* Includes CO_2 equivalent VOC and CO emissions

Table 2.20 Upstream GHG Emissions from Residual Oil Refining, g/mmBtu

	VOC	CO	CH_4	N_2O	CO_2	CO_2*	GHG	GHG gCO_2e/MJ
Residual Oil	0.019	0.042	0.271	0.004	23.376	23.499	31.008	0.029
Natural Gas	0.043	0.079	0.918	0.001	35.191	35.450	56.947	0.054
Electricity	0.213	1.367	3.261	1.085	2055.687	2058.500	2454.588	2.327
Refinery Gas	0	0	0	0	0	0.000	0.000	0.000
Total	**0.275**	**1.487**	**4.450**	**1.090**	**2114.254**	**2117.449**	**2542.544**	**2.410**

* Includes CO_2 equivalent VOC and CO emissions

Table 2.21 Total (direct + upstream) GHG Emissions from Residual Oil Refining, g/mmBtu

	VOC	CO	CH_4	N_2O	CO_2	CO_2*	GHG	GHG gCO_2e/MJ
Residual Oil	0.021	0.086	0.280	0.005	263.817	264.018	272.038	0.258
Natural Gas	0.054	0.212	0.931	0.005	419.060	419.560	442.538	0.419
Electricity	0.213	1.367	3.261	1.085	2055.687	2058.500	2454.588	2.327
Refinery Gas	0.036	0.475	0.045	0.014	1370.961	1371.821	1377.108	1.305
Non-Combustion	2.078	1.039			376.714	384.825	384.825	0.365
Total	**2.403**	**3.179**	**4.51**	**1.11**	**4486.24**	**4498.724**	**4931.098**	**4.674**

* Includes CO_2 equivalent VOC and CO emissions

2.14 Residual Oil Transport

The last step of the residual oil pathway is transport from the refinery to final destination. The GREET default modes and distances are utilized as indicated in Table 2.22.

Table 2.22 Residual Oil Transport Mode Shares, Miles and Process Fuels (all GREET Defaults)

Mode	Mode Share	Miles	Analysis Miles	Fuel
Ocean Tanker	24%	3,000	720	Residual Oil
Barge	40%	340	136	Residual Oil
Pipeline	60%	400	240	20% Diesel, 50% Residual Oil, 24% Natural Gas, 6% Electric
Rail	5%	800	40	Diesel

Residual Oil Transport Energy Consumption

Details of how energy use is calculated for each transport mode are detailed in Table 2.23 below with values used in the calculation provided in Table 2.24. Both modes utilize common factors such as lower heating values (LHV) and density of residual oil, and transport mode specific factors such as energy consumed per mile of transport to calculate energy use for specific distances transported.

Table 2.23 Details of Energy Consumed for Residual Oil Transport

	Detailed Calculations	Btu/mmBtu
Ocean Tanker	(Density of residual oil/LHV of residual oil)*(Energy Intensity)*(miles)/(454*2000)* (1+WTT Residual Oil)*10^6	1,696
Barge	(Density of residual oil/LHV of residual oil)*(Energy Intensity)*(miles)*/(454*2000)*(1+WTT Residual Oil)*10^6	3,149
Pipeline	(Density of residual oil/LHV of residual oil)*(Energy Intensity)*(miles)/(454*2000)*(24%*WTT NG + 20%* WTT Diesel + 50%*WTT Resid + 6%*WTT Electricity)*10^6	2,112
Rail	(Density of residual oil/LHV of residual oil)*(Energy Intensity)*(miles)*/(454*2000)*(1+WTT Diesel)*10^6	513
Total		**7,470**

Table 2.24 Values for Formulas in Table 2.23

Description	Value	Source
Ocean tanker miles	720	GREET default
Barge miles	136	GREET default
Pipeline transport miles	240	GREET default
Rail transport miles	40	GREET default
Density of residual oil (grams/gallon)	3,752	GREET default
Lower heating value (LHV) of residual oil (Btu/gal)	140,353	GREET default
Ocean tanker energy intensity (Btu/ton-mile)	72	GREET calculation
Barge energy intensity (Btu/ton-mile)	710	GREET calculation
Pipeline energy intensity (Btu/ton-mile)	253	GREET calculation
Rail energy intensity (Btu/ton-mile)	513	GREET calculation
Conversion from pounds to grams	454	
Conversion from tons to pounds	2000	
WTT Energy Factor for Residual Oil, Btu/Btu	0.107	GREET calculation
WTT Energy Factor for Electricity, Btu/Btu	2.279	GREET calculation
WTT Energy Factor for Diesel, Btu/Btu	0.177	GREET calculation
WTT Energy Factor for Natural Gas, Btu/Btu	0.073	GREET calculation

Note that the total residual oil refining and transport energy is 66,767 + 7,470 = 74,237 Btu/mmBtu. This is the total energy associated with crude recovery and transport for this pathway. This is the value used in Table 1.04 (also shown in table 2.01) to calculate the upstream energy associated with residual oil used for electricity production.

Residual Oil Transport Emissions

Table 2.25 details CO_2 emissions related to residual oil transport and distribution. Table 2.26 provides values for various terms used in Table 2.25. Total GHG emissions are provided in Table 2.27.

Table 2.25 Residual Oil Transport CO_2 Emissions

Mode	Formula	gCO_2/mmBtu	gCO_2/MJ
Ocean Tanker	(Density of residual oil/LHV of residual oil)*(miles) /(454*2000)*((Energy intensity on trip from origin to destination*(emission factor for bunker fuel + WTT CO_2 for residual oil)) + (Energy intensity on return trip*(emission factor for bunker fuel + WTT CO_2 for residual oil))	142	0.14
Barge	(Density of residual oil/LHV of residual oil)*(miles) /(454*2000)*((Energy intensity on trip from origin to destination*(emission factor for residual oil boiler + WTT CO_2 for residual oil)) + (Energy intensity on return trip*(emission factor for boiler residual oil + WTT CO_2 for residual oil))	265	0.25
Pipeline	(Density of residual oil/LHV of residual oil)*(Energy intensity of pipeline)*(miles)/(454*2000) * (turbine share * (% NG * (NG turbine emission factor + NG WTT) + % electricity * WTT electricity + % diesel * (diesel turbine emission factor + WTT diesel) + % residual oil * (resid oil turbine emission factor + WTT resid oil) + current engine share *(% NG * (NG engine emission factor + NG WTT) + % electricity * WTT electricity + % diesel * (diesel engine emission factor + WTT diesel) + % residual oil * (resid oil engine emission factor + WTT resid oil) + future engine share * (% NG * (NG future engine emission factor + NG WTT) + % electricity * WTT electricity + % diesel * (diesel future engine emission factor + WTT diesel) + % residual oil * (resid oil future engine emission factor + WTT resid oil))	158	0.15
Rail	(Density of residual oil/LHV of residual oil)*(miles) /(454*2000)*((Energy intensity on trip from origin to destination*(emission factor for diesel locomotive + WTT CO_2 for diesel)) + (Energy intensity on return trip*(emission factor for diesel locomotive + WTT CO_2 for diesel))	39	0.04
Total		**604**	**0.57**

Table 2.26 Values of Properties Used in Table 2.25

Parameter	Value	Source
Ocean tanker miles (one way)	720	GREET default
Barge miles (one way)	136	GREET default
Pipeline transport miles (one way)	240	GREET default
Rail transport miles (one way)	40	GREET default
Density of residual oil (grams/gallon)	3,752	GREET default
Lower heating value (LHV) of residual oil (Btu/gal)	140,353	GREET default
Energy intensity of ocean tanker to destination (Btu/ton-mile)	38	GREET calculation
Energy intensity of ocean tanker on return trip (Btu/ton-mile)	34	GREET calculation
Energy intensity of barge on trip to destination (Btu/ton-mile)	403	GREET calculation
Energy intensity of barge on return trip (Btu/ton-mile)	307	GREET calculation
Energy intensity of pipeline (Btu/ton-mile)	253	GREET calculation
Energy intensity of rail (Btu/ton-mile)	370	GREET calculation
Conversion from pounds to grams	454	
Conversion from tons to pounds	2,000	
Conversion from MJ to mmBtu	1,055	
CO_2 emission factor for bunker fuel to destination, g/mmBtu	84,515	GREET default
CO_2 emission factor for bunker fuel return trip, g/mmBtu	84,515	GREET default
CO_2 emission factor for residual Oil boiler, g/mmBtu	84,048	GREET default
CO_2 emission factor for residual oil turbine, g/mmBtu	85,061	GREET default
CO_2 emission factor for residual oil current engine, g/mmBtu	84,219	GREET default
CO_2 emission factor for residual oil future engine, g/mmBtu	84,219	GREET default
CO_2 emission factor for diesel turbine, g/mmBtu	78,179	GREET default
CO_2 emission factor for diesel current engine, g/mmBtu	77,337	GREET default
CO_2 emission factor for diesel future engine, g/mmBtu	77,337	GREET default
CO_2 emission factor for natural gas turbine, g/mmBtu	58,179	GREET default
CO_2 emission factor for natural gas current engine, g/mmBtu	56,013	GREET default
CO_2 emission factor for natural gas future engine, g/mmBtu	56,551	GREET default
WTT emissions for residual oil, Btu/Btu	8,268	GREET calculation
WTT emissions for diesel, Btu/Btu	12,743	GREET calculation
WTT emissions for natural gas, Btu/Btu	5,335	GREET calculation
WTT emissions for electricity	145,421	GREET calculation

Table 2.27 Total GHG Emissions Residual Oil Transport and Distribution

GHG	(g/mmBtu)	Formula to convert to CO_2e	$gCO_2e/mmBtu$	GHG gCO_2e/MJ
CO_2	604	604*1	604	0.57
CH_4	0.753	0.753*23	17.32	0.02
N_2O	0.030	0.030*296	8.88	0.01
CO	1.167	1.167*0.43*(44/12)	1.84	0.00
VOC	0.373	0.373*0.85*(44/12)	1.16	0.00
Total GHG emissions			**617**	**0.58**

Note that total CO_2 emissions for residual oil refining and transport (including CO and VOC) are 606 + 4,499 = 5,105 g/mmBtu of crude oil. This is the value shown in Table 2.01 to calculate upstream CO_2 emissions for residual oil used in electricity generation.

2.2 Coal

The energy and emissions associated with coal may be divided into two main activities: coal mining and coal transport. Table 2.28 provides a summary of the energy and emissions for supplying coal as a feedstock to electric power plants. Note that the values for total energy and total CO_2 emissions shown in Table 2.28 are the same as those indicated in Table 2.01.

Table 2.28 Summary of the Coal Feedstock for Electricity Production Pathway

	Energy Use Btu/mmBtu	CO_2* Emissions $gCO_2/mmBtu$	GHG Emissions gCO_2e/MJ
Mining	4,091	308.142	3.017
Transport	12,139	944.915	0.964
Pathway Total	**16,230**	**1,253.057**	**3.981**

* Includes CO_2 equivalent VOC and CO emissions

2.21 Coal Mining

Coal Mining Energy

As per standard GREET methodology, the energy consumed in coal mining set by specifying process efficiency and fuel shares. The process efficiency assumed in the AB1007 analysis is 99.8%, higher than the GREET default value of 99.3%. The AB1007 fuel shares are also significantly different; the GREET Default values had much higher diesel and much lower electric shares than those utilized for AB1007. The AB1007 data is based on more recent information from EIA and the U.S. Census Bureau. Please refer to the AB1007 WTT report section 3 [Error! Bookmark not defined.] for details.

Table 2.29 Calculating Direct Energy Consumption for Coal Mining Operations

Fuel Type	Fuel Shares	Calculating Direct Fuel Consumption from Efficiency (0.955) and Fuel Shares	Direct Fuel Consumption Btu/mmBtu Residual Oil
Residual Oil	14%	(1,000,000)(1/0.998 – 1)(0.14)	309
Diesel	9%	(1,000,000)(1/0.998 – 1) (0.09)	198
Gasoline	2%	(1,000,000)(1/0.998 – 1) (0.02)	44
Natural Gas	2%	(1,000,000)(1/0.998 – 1) (0.02)	44
Coal	9%	(1,000,000)(1/0.998 – 1) (0.09)	198
Electricity	64%	(1,000,000)(1/0.998 – 1)(0.64)	1,411
Total Direct Energy Consumption for Residual Oil Refining			**2,205**

The values in Table 2.29 only represent the direct fuel consumption. We need to account for the energy consumed to recovery and produce these process fuels, the upstream energy. Table 2.30 illustrates the equations used to determine total fuel consumption for crude refining to residual oil. Table 2.31 details the values and descriptions for the formulas presented in Table 2.30

Table 2.30 Calculation of Total Fuel Consumption from Direct Fuel Consumption

Fuel Type	Formula	Btu/mmBtu
Residual Oil	$309*(1 + (A*B+C)/10^6)$	342
Diesel	$198*(1 + (A*D+E)/10^6)$	234
Gasoline	$44*(1 + (A*F+G)/10^6)$	54
Natural Gas	$44*(1 + H/ 10^6)$	47
Coal	$198*(1+I/ 10^6)$	199
Electricity	$2205*(J + K)/ 10^6)$	3,215
Total (direct + upstream) energy for residual oil refining		**4,091**

Table 2.31 Details for Entries in Table 2.30

Quantity	Description
A = 33,220	Energy required to produce and transport crude as feedstock for use in US refineries, a GREET calculated value.
B = 1.000	Residual Oil Loss factor, a GREET default.
C = 74,237	Energy (Btu/mmBtu of residual oil) to refine and transport residual oil, a GREET calculated value.
D = 1.000	Diesel Loss Factor, a GREET default.
E = 143,899	Energy (Btu/mmBtu of diesel) to refine and transport diesel, a GREET calculated value.
F = 1.000	Conventional gasoline loss factor, a GREET default
G = 184,474	Energy (Btu/mmBtu of gasoline) to refine and transport gasoline, a GREET calculated value.
H = 73,495	Energy (Btu/mmBtu of natural gas) required to recover, process and transport natural gas as a stationary fuel, a GREET calculated value.
I = 4,091	Energy (Btu/mmBtu of coal) required to recover, process and transport coal as a stationary fuel, a GREET calculated value. This is an example of a GREET iterative calculation.
J = 105,317	Total energy (Btu/mmBtu of electricity) required to recover, process and transport all feedstocks used to generation electricity, a GREET calculated value.
K = 2,173,356	Energy required in Btu to produce one million Btu of electricity, a GREET calculated value.

Coal Mining Emissions

The coal mining emissions are calculated from direct fuel use. The fuel is assumed split among different combustion devices as shown in Table 2.32. Table 2.33 provides direct emissions (direct fuel splits multiplied by GREET default emission factors). Table 2.34 provides the upstream emissions associated with recovery, processing and transport of the direct fuel consumed. Finally, Table 2.35 summarizes total emissions associated with coal mining.

Table 2.32 Coal Mining Direct Fuel Consumption Splits

	Industrial Boiler	Commercial Boiler	Engine	Turbine
Residual Oil		100%		
Diesel		33%	33%	34%
Gasoline			100%	
Natural Gas		50%	50%	
Coal	100%			

Table 2.33 Direct Emissions for Coal Mining, g/mmBtu

	VOC	CO	CH_4	N_2O	CO_2
Residual Oil	0.000	0.005	0.000	0.000	26.253
Diesel	0.006	0.025	0.001	0.000	15.458
Gasoline	0.078	0.577	0.004	0.000	2.226
Natural Gas	0.001	0.008	0.008	0.000	2.530
Coal	0.000	0.015	0.001	0.000	27.262
Electricity	0	0	0	0	0
Non-combustion	6.903		117.906		
Total	**6.989**	**0.630**	**117.921**	**0.001**	**73.729**

Table 2.34 Upstream Emissions for Coal Mining, g/mmBtu

	VOC	CO	CH_4	N_2O	CO_2
Residual Oil	0.002	0.005	0.030	0.000	2.552
Diesel	0.001	0.003	0.020	0.000	2.529
Gasoline	0.001	0.001	0.005	0.000	0.751
Natural Gas	0.000	0.001	0.006	0.000	0.235
Coal	0.001	0.000	0.023	0.000	0.057
Electricity	0.021	0.136	0.326	0.108	205.204
Non-combustion	0	0	0	0	0
Total	**0.027**	**0.146**	**0.409**	**0.109**	**211.327**

Table 2.35 Total GHG Emissions for Coal Mining, g/mmBtu

	VOC	CO	CH_4	N_2O	CO_2	GHG	GHG, g/MJf
Residual Oil	0.002	0.009	0.030	0.001	28.805	29.690	0.029
Diesel	0.007	0.029	0.021	0.000	17.987	18.664	0.018
Gasoline	0.079	0.578	0.009	0.000	2.977	4.379	0.004
Natural Gas	0.001	0.009	0.014	0.000	2.765	3.126	0.003
Coal	0.002	0.015	0.024	0.000	27.318	27.946	0.028
Electricity	0.021	0.136	0.326	0.108	205.204	245.023	0.241
Non-combustion	6.903	0.000	117.906	0.000	0.000	2733.364	2.693
Total	**7.016**	**0.776**	**118.330**	**0.110**	**285.056**	**3062.192**	**3.017**

2.22 Coal Transport

The energy and emissions associated with coal transport are based on assumptions of mode share and miles. Table 2.36 provides the default GREET mode shares and miles for coal transport to power plants.

Table 2.36 Coal Transport Modes, Miles and Fuels

	Mode Share	Miles	Actual Miles	Fuel
Barge	10%	330	33	Residual Oil
Rail	90%	440	396	Diesel

Coal Transport Energy

Table 2.37 illustrates the energy calculations and Table 2.38 provides the values for the equations in Table 2.37.

Table 2.37 Details of Energy Consumed for Coal Transport

	Detailed Calculations	Btu/mmBtu
Barge	(Energy Intensity)*(miles)*(1+WTT of residual oil)/(LHV of coal)*10^6	955
Rail	(Energy Intensity)*(miles)*(1+WTT of diesel)/(LHV of coal)*10^6	11,184
Total		**12,139**

Table 2.38 Values for Formulas in Table 2.37

Description	Value	Source
Barge miles	33	GREET default
Rail transport miles	396	GREET default
Lower heating value (LHV) of coal (Btu/ton)	15,421,670	GREET default
Barge energy intensity (Btu/ton-mile)	403	GREET calculation
Rail energy intensity (Btu/ton-mile)	370	GREET calculation
WTT Energy Factor for Residual Oil, Btu/Btu	0.107	GREET calculation
WTT Energy Factor for Diesel, Btu/Btu	0.177	GREET calculation

Note that the total coal energy (mining plus transport) is 16,230 Btu/mmBtu. This is the value used in Table 1.04 to calculate the upstream energy associated with coal use for electricity production.

Coal Transport GHG Emissions

Table 2.39 provides the emissions associated with transporting coal by rail and barge to the power plants.

Table 2.39 Coal Transport Emissions, g/mmBtu

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**	**GHG**	**GHG gCO_2e/MJ**
Barge, g/ton	0.604	1.572	1.301	0.047	1,237.447	1,285.569	1.267
Rail, g/ton	9.853	33.884	15.287	0.422	13,246.41	13,806.75	13.603
Total, g/ton	10.457	35.456	16.588	0.468	14,483.856	15,092.32	14.869
Barge, g/mmBtu	0.039	0.102	0.084	0.003	80.241	83.361	0.082
Rail, g/mmBtu	0.639	2.197	0.991	0.027	858.948	895.282	0.882
Total, g/mmBtu	**0.678**	**2.3**	**1.076**	**0.03**	**939.19**	**978.64**	**0.964**

2.3 Biomass

The GREET model assumes that biomass used for electricity production comes from farmed trees. Table 2.40 provides a summary of the energy and emissions for each component of the Biomass as an electricity feedstock process. Note that the total energy value is used to calculate upstream energy associated with biomass feedstock. Similarly, the total CO_2 value is used to calculate biomass upstream CO_2 emissions from biomass feedstock. The energy and CO_2 values in Table 2.40 are the same as those shown in Table 2.01.

It should be mentioned that in California, farmed trees are not utilized for biomass electricity production. The biomass utilized in California for electricity production is generally waste biomass such as agricultural waste, forest residue and sawdust. As a result, the energy and emissions associated with biomass feedstock preparation are overstated here – the energy and emissions associated with farm chemical use (fertilizers, pesticides and herbicides) should be removed. As can be seen, farm chemicals only contribute a small fraction to total energy. However the contribution to GHG emissions is approximately 17%, mainly due to the amount of N_2O assumed emitted subsequent to nitrogen fertilizer application.

Table 2.40 Total Energy Consumption and Emissions for Biomass as an Electricity Production Feedstock

	Energy Required (Btu/ton)	**Emissions, g/ton**				
		CH_4	N_2O	CO_2	CO_2*	CO_2e
Farming	291,093	27.368	1.473	21,866	22,087	23,153
Farm Chemicals	43,22	2.699	18.096	2,420	2,442	7,860
Biomass Transport	189,742	16.392	0.464	14,594	14,666	15,181
Total	**524,057**	**46.46**	**20.03**	**38,880**	**39,19**	**46,19**

* Includes CO_2 equivalent VOC and CO emissions

2.31 Biomass Farming

Biomass Farming Energy Use

The farming energy consumption is set by an assumed energy intensity of 234,770 Btu/ton of biomass produced. The process fuel shares and direct energy consumption are provided in Table 2.41.

Table 2.41 Direct Energy Use in Tree Farming

Fuel Type	Fuel Shares	Calculating Direct Fuel Consumption	Direct Fuel Consumption Btu/g U-235
Diesel	94.3%	(234,770) * (0.943)	221,388
Electricity	5.7%	(234,770) * (0.057)	13,382
Total Direct Energy Consumption for Tree Farming			**234,770**

The values in Table 2.41 only represent the direct fuel consumption. We need to account for the energy consumed to recovery and produce these process fuels, the upstream energy. Table 2.42 illustrates the equations used to determine total fuel consumption for tree farming. Table 2.43 details the values and descriptions for the formulas presented in Table 2.42.

Table 2.42 Calculation of Total Fuel Consumption from Direct Fuel Consumption

Fuel Type	Formula	Btu/ton
Diesel	$221,388 * (1 + (A*B+C)/10^6)$	52,826
Electricity	$13,382 * (D + E)/ 10^6)$	96,155
Total (direct + upstream) energy for tree farming		**237,221**

Table 2.43 Details for Entries in Table 2.42

Quantity	Description
A = 33,220	Energy required to produce and transport crude as feedstock for use in US refineries, a GREET calculated value.
B = 1.000	Diesel Loss factor, a GREET default.
C = 143,899	Energy (Btu/mmBtu of diesel) to refine and transport diesel, a GREET calculated value.
D = 105,317	Total energy (Btu/mmBtu of electricity) required to recover, process and transport all feedstocks used to generation eletctricity, a GREET calculated value.
E = 2,173,356	Energy required in Btu to produce one million Btu of electricity, a GREET calculated value.

Biomass Farming GHG Emissions

The farming emissions consist of direct and upstream diesel emissions plus upstream electricity emissions. Table 2.44 provides the farming emissions.

Table 2.44 GHG Emissions from Tree Farming, g/ton

	VOC	CO	CH_4	N_2O	CO_2
Direct Emissions					
Diesel	22.766	87.334	2.054	0.251	17,098.499
Electricity	0.000	0.000	0.000	0.000	0.000
Total Direct	22.766	87.334	2.054	0.251	17,098.499
Upstream Emissions					
Diesel	1.670	3.599	22.227	0.194	2821.047
Electricity	0.202	1.294	3.087	1.027	1946.005
Total Upstream	1.872	4.893	25.313	1.221	4,767.052
Total Farming Emissions					
Diesel	24.436	90.933	24.281	0.446	19,919.546
Electricity	0.202	1.294	3.087	1.027	1,946.005
Total Farming	**24.638**	**92.226**	**27.368**	**1.473**	**21,865.55**

2.32 Farm Chemical Use

Farm Chemical Energy Use

The energy and emissions associated with farm chemical use are almost entirely upstream energy and emissions associated with chemical production and transport. The farm chemical use is therefore determined by an assumed usage rate multiplied by the production and transport values. The energy and emissions associated with production and transport of each farm chemical are presented in the Ethanol Pathway report and the reader may consult this document for the assumptions on production and transport of farm chemicals. The farming chemical use rate and resulting energy consumption for tree farming are provided in Table 2.45.

Table 2.45 Energy Associated with Farm Chemical Use

Product Type	Use Rate, g/ton	Energy Consumption, Btu/ton
Nitrogen	709	32,174
P2O5	189	2,405
K2O	331	2,575
Herbicide	24	6,061
Insecticide	2	6
Total	**1,255**	**43,222**

Farm Chemical GHG Emissions

Similarly, the emissions associated with farm chemical application are purely upstream emissions with the exception of N_2O emissions due to nitrogen fertilizer application. Table 2.46 provides the GHG emissions associated with farm chemical use.

Table 2.46 Emissions from Farm Chemical Use, g/ton

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**
Nitrogen	4.300	4.068	1.512	1.239	1,608.308
P_2O_5	0.064	0.195	0.263	0.026	161.664
K_2O	0.038	0.155	0.262	0.047	173.833
Herbicide	0.061	0.273	0.603	0.065	434.509
Insecticide	0.008	0.034	0.059	0.007	41.914
N_2O from N Fertilizer Application				16.712	
Total	**4.471**	**4.725**	**2.699**	**18.096**	**2,420.23**

<u>2.33 Biomass Transport</u>

Biomass Transport Energy Use

The GREET default assumptions for farmed tree transport to the electric power plant are as follows:

Distance:	40 miles (one-way)
Mode:	Heavy Duty Diesel Truck
Truck Payload:	17 tons
Truck Energy Consumption:	25,690 Btu/mi

The direct truck energy for the trip to the power plant and back is calculated as:

Direct Energy = 25,690 Btu/mi / 17 tons/load * 2 * 40 miles = 120,894 Btu/ton

The upstream energy is the direct energy multiplied by the upstream diesel factor (energy to recover, refine and transport diesel):

Upstream energy = 120,894 Btu/ton * 0.177 Btu/Btu diesel = 21,413 Btu/ton

These values are for dry biomass. It is assumed that the transported biomass has 25% more moisture than the biomass utilized at the power plant. Therefore, the total transport energy is:

Total transport energy = (120,894 Btu/ton + 21,413 Btu/ton) / (1-25%) = 189,742 Btu/ton

Biomass Transport GHG Emissions

The transport emissions are determined using the EMFAC emissions factors for heavy duty diesel trucks. The direct, upstream and total emissions are provided in Table 2.47.

Table 2.47 GHG Emissions from Farmed Tree Transport, g/ton

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**
Direct Emissions	5.525	19.596	0.156	0.242	9,405.363
Upstream Emissions	0.912	1.965	12.137	0.106	1,540.498
Total Transport	**6.437**	**21.56**	**12.29**	**0.35**	**10,945.86**
Moisture Corrected Total	**8.58**	**28.75**	**16.39**	**0.46**	**14,594.48**

2.4 Nuclear

The nuclear power plant feedstock is uranium. GREET default values were exclusively utilized throughout. It is assumed that only light water reactors (LWR) are utilized. The pathway may be broken down into five steps:

- Uranium Mining
- Uranium Ore Transport
- Uranium Enrichment
- Uranium Conversion, Fabrication and Waste Storage
- Uranium Fuel Transport

Table 2.48 provides a summary of the energy consumption and emissions of the nuclear pathway.

Table 2.48 Summary of the Nuclear Feedstock for Electricity Production Pathway

	Energy		**CO_2* Emissions**	**GHG Emissions**	
	Btu/g U-235	Btu/mmBtu	g/g U-235	gCO_2e/g U235	gCO_2e/mmBtu
Mining	237,221	0.010	15,713.938	17,630.640	0.001
Ore Transport	629	0.000	48.626	50.331	0.000
Enrichment	766,697	0.032	48,996.173	58,423.831	0.002
Enriched Uranium Transport	104	0.000	8.006	8.287	0.000
Uranium Conversion	90,550	0.004	5,567.405	6,465.109	0.000
Uranium Transport	80	0.000	6.181	6.398	0.000
Pathway Total	**1,095,281**	**0.046**	**70,340.328**	**82,584.595**	**0.003**

* Includes CO_2 equivalent VOC and CO emissions

Note that all uranium values are calculated per gram of U-235 produced. To convert to a per mmBtu basis, we divide by 6.926 MWh per gram of U-235. This is converted to mmBtu by multiplying by 3.412 and 10^6:

g/mmBtu = (g/g U-235) / (6.926 MWh/g U-235) / 3412 Btu/kWh / 1000 kWh/MWh

Note that the Uranium Pathway total energy (1,095,281 Btu/g U-235) and total CO_2 emission values (70,340) are the same as the values shown in Tale 2.01.

2.41 Uranium Mining

Uranium Mining Energy Use

The uranium mining energy consumption is set by an assumed energy intensity of 167,452 Btu/g U-235 recovered. The process fuel shares and direct energy consumption are provided in Table 2.49.

Table 2.49 Direct Energy Use in Uranium Mining

Fuel Type	**Fuel Shares**	**Calculating Direct Fuel Consumption**	**Direct Fuel Consumption Btu/g U-235**
Diesel	26.8%	(167,452) * (0.268)	44,877
Gasoline	8.1%	(167,452) * (0.081)	13,564
Natural Gas	39.9%	(167,452) * (0.399)	66,813
Electricity	25.2%	(167,452) * (0.252)	42,198
Total Direct Energy Consumption for Uranium Mining			**167,452**

The values in Table 2.49 only represent the direct fuel consumption. We need to account for the energy consumed to recovery and produce these process fuels, the upstream energy. Table 2.50 illustrates the equations used to determine total fuel consumption for uranium mining. Table 2.51 details the values and descriptions for the formulas presented in Table 2.50.

Table 2.50 Calculation of Total Fuel Consumption from Direct Fuel Consumption

Fuel Type	**Formula**	**Btu/g U-235**	**Btu/mmBtu**
Diesel	$44,877*(1 + (A*B+C)/10^6)$	52,826	0.002
Gasoline	$13,564*(1 + (A*D+E)/10^6)$	16,516	0.001
Natural Gas	$66,813*(1 + F/ 10^6)$	71,724	0.003
Electricity	$42,197*(G + H)/ 10^6)$	96,155	0.004
Total (direct + upstream) energy for uranium mining		**237,221**	**0.010**

Table 2.51 Details for Formulas in Table 2.50

Quantity	**Description**
A = 33,220	Energy required to produce and transport crude as feedstock for use in US refineries, a GREET calculated value.
B = 1.000	Diesel Loss factor, a GREET default.
C = 143,899	Energy (Btu/mmBtu of diesel) to refine and transport diesel, a GREET calculated value.
D = 1.000	Gasoline Loss Factor, a GREET default.
E = 184,474	Energy (Btu/mmBtu of gasoline) to refine and transport gasoline, a GREET calculated value.
F = 73,495	Energy (Btu/mmBtu of natural gas) required to recover, process and transport natural gas as a stationary fuel, a GREET calculated value.
G = 105,317	Total energy (Btu/mmBtu of electricity) required to recover, process and transport all feedstocks used to generation eletctricity, a GREET calculated value.
H = 2,173,356	Energy required in Btu to produce one million Btu of electricity, a GREET calculated value.

Uranium Mining GHG Emissions

The emissions associated with mining operations are split into direct emissions from direct fuel combustion and upstream emissions associated with recovery and processing of the process fuels. The direct, upstream and total emissions are provided in Tables 2.52 to 2.54.

Table 2.52 Direct Emissions from Uranium Mining, g/g U-235

	VOC	CO	CH_4	N_2O	CO_2	CO_2*	GHG
Diesel	1.273	5.743	0.136	0.066	3,495.985	3,508.976	3,531.604
Gasoline	24.091	177.406	1.331	0.033	684.689	1,038.555	1,078.812
Natural Gas	1.454	12.403	12.362	0.061	3,832.616	3,856.639	4,158.908
Electricity	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	**26.82**	**195.55**	**13.83**	**0.16**	**8,013.29**	**8,404.170**	**8,769.32**

* Includes CO_2 equivalent VOC and CO emissions

Table 2.53 Upstream Emissions from Uranium Mining, g/g U-235

	VOC	CO	CH_4	N_2O	CO_2	CO_2*	GHG
Diesel	0.339	0.730	4.505	0.039	571.849	574.050	689.328
Gasoline	0.159	0.254	1.396	0.014	230.934	231.828	268.004
Natural Gas	0.439	0.798	9.299	0.013	356.420	359.041	576.767
Electricity	0.637	4.079	9.734	3.238	6,136.452	6,144.849	7,327.217
Total	**1.57**	**5.86**	**24.93**	**3.304**	**7,295.65**	**7,309.768**	**8,861.32**

* Includes CO_2 equivalent VOC and CO emissions

Table 2.54 Total Emissions from Uranium Mining, g/g U-235

	VOC	CO	CH_4	N_2O	CO_2	CO_2*	GHG
Diesel	1.612	6.472	4.641	0.105	4,067.833	4083.026	4,220.932
Gasoline	24.250	177.660	2.727	0.046	915.623	1270.383	1,346.816
Natural Gas	1.893	13.201	21.660	0.074	4,189.036	4215.680	4,735.675
Electricity	0.637	4.079	9.734	3.238	6,136.452	6144.849	7,327.217
Total	**28.39**	**201.41**	**38.76**	**3.46**	**15,308.94**	**15,713.938**	**17,630.64**

* CO_2 includes VOC and CO

2.42 Uranium Ore Transport

Uranium Ore Transport Energy

The uranium ore is transported from the mine to the enrichment facility by truck. The default distance is 1,360 miles. The total energy to transport the ore is calculated with the following formula:

Transport Energy Btu/ton ore = Miles * Energy Intensity (Btu/ton-mile) * (1 + WTT of diesel)

The values for this equation are presented in Table 2.55

Table 2.55 Uranium Ore Transport Energy

Parameter	Value	Reference
Truck miles	1,360	GREET Default
Truck Energy Intensity, Btu/ton-mile	1,028	GREET calculated value
WTT energy of diesel fuel, Btu/Btu	0.177	GREET calculated value
Transport Energy, Btu/ton ore	1,645,067	GREET calculated value
Uranium Yellow Cake to U-235 Conversion Factor	0.29%	GREET Default
Transport Energy, Btu/g U-235	629	GREET calculated value

Uranium Ore Transport GHG Emissions

The emissions associated with truck transport of uranium ore to the enrichment facility are determined as follows:

$$\text{Emissions g/ton ore} = (A + B) * C * D / 10^6$$

where the parameters are described in Table 2.56. Resulting emissions in g/ton ore are converted utilizing the conversion factor indicated in Table 2.56. Table 2.57 provides ore transport emissions on a per g U-235 basis.

Table 2.56 Values of Properties Used to Calculate Ore Transport Emissions

Parameter	Source
A = diesel truck emission factor, g/mmBtu	AB1007 value
B = WTT diesel emissions g/mmBtu	GREET calculation
C = truck transport energy intensity, Btu/ton-mile	GREET calculation
D = transport miles	GREET default

Table 2.57 Total GHG Emissions Uranium Ore Transport to Enrichment Facility, g/g U-235

GHG	(g/g U-235)	Formula to convert to CO_2e	gCO_2e/g U-235
CO_2	48	48*1	48
CH_4	0.054	0.054*23	1.24
N_2O	0.002	0.002*296	0.59
CO	0.095	0.095*0.43*(44/12)	0.15
VOC	0.028	0.028*0.85*(44/12)	0.09
CO_2*	**48.626**		
Total GHG emissions			**50**

* Includes CO_2 equivalent VOC and CO emissions

2.43 Uranium Enrichment

Uranium Enrichment Energy Use

The uranium enrichment energy consumption is set by an assumed (GREET default) energy intensity of 336,466 Btu/g U-235 recovered. It is further assumed that only electricity is used in the enrichment process. This is only the direct fuel consumption. We need to account for the energy consumed to recovery and produce the feedstocks to generate this electricity. The total energy consumption is calculated as follows:

Total Energy, Btu/g U-235 = A * (B+C)/10^6

The total energy for uranium enrichment is 766,697 Btu/g U-235. Table 10 provides the values and descriptions of the parameters in the above formula.

Table 2.58 Details for Total Enrichment Energy Consumption

Quantity	Description
A = 336,466	Energy (100% electricity) required to enrich uranium, Btu/g U-235
B = 105,317	Total energy (Btu/mmBtu of electricity) required to recover, process and transport all feedstocks used to generation electricity, a GREET calculated value.
C = 2,173,356	Energy required in Btu to produce one million Btu of electricity, a GREET calculated value.

Uranium Enrichment GHG Emissions

Because electricity consumption does not result in any direct emissions, the only emissions associated with enrichment are upstream emissions from electricity feedstocks and production. Table 11 provides the total emissions associated with uranium enrichment.

Table 2.59 Total Emissions from Uranium Enrichment, g/g U-235

	VOC	CO	CH_4	N_2O	CO_2	CO_2*	GHG
Electricity	5.081	32.528	77.615	25.819	48,929.223	48,996.173	58,423.831

* Includes CO_2 equivalent VOC and CO emissions

2.44 Uranium Conversion, Fabrication and Waste Storage

Uranium Conversion, Fabrication and Waste Storage Energy Use

The energy and emissions associated with uranium conversion, fabrication and storage of waste are dictated by an assumed process energy intensity and fuel split. The process energy intensity is assumed to be 60,801 Btu/g U-235. Table 2.60 illustrates how the direct energy is split.

Table 2.60 Direct Energy Use in Uranium Mining

Fuel Type	Fuel Shares	Calculating Direct Fuel Consumption	Direct Fuel Consumption Btu/g U-235
Natural Gas	65.5%	(60,801) * (0.399)	39,825
Electricity	34.5%	(60,801) * (0.252)	20,977
Total Direct Energy Consumption for Uranium Conversion			**60,801**

The values in Table 2.60 only represent the direct fuel consumption. We need to account for the energy consumed to recovery and produce these process fuels, the upstream energy. Table 2.61 illustrates the equations used to determine total fuel consumption for uranium mining. Table 2.62 details the values and descriptions for the formulas presented in Table 2.61.

Table 2.61 Calculation of Total Fuel Consumption from Direct Fuel Consumption

Fuel Type	Formula	Btu/g U-235
Natural Gas	$39,825*(1 + A/ 10^6)$	42,752
Electricity	$20,977*(B + C)/ 10^6)$	47,799
Total (direct + upstream) energy		**90,550**

Table 2.62 Details for Formulas in Table 2.61

Quantity	Description
A = 73,495	Energy (Btu/mmBtu of natural gas) required to recover, process and transport natural gas as a stationary fuel, a GREET calculated value.
B = 105,317	Total energy (Btu/mmBtu of electricity) required to recover, process and transport all feedstocks used to generation electricity, a GREET calculated value.
C = 2,173,356	Energy required in Btu to produce one million Btu of electricity, a GREET calculated value.

Uranium Conversion, Fabrication and Waste Storage GHG Emissions

The emissions associated with uranium conversion operations are split into direct emissions from direct fuel combustion and upstream emissions associated with recovery and processing of the process fuels. The direct, upstream and total emissions are provided in Tables 2.62 to 2.64.

Table 2.62 Direct Emissions from Uranium Conversion, Fabrication and Waste Storage, g/g U-235

	VOC	CO	CH_4	N_2O	CO_2	CO_2*	GHG
Natural Gas	0.867	7.393	7.368	0.036	2284.481	2298.800	2478.971
Electricity	0	0	0	0	0	0	0
Total	**0.87**	**7.39**	**7.37**	**0.036**	**2,284.48**	**2,298.8**	**2,478.97**

* Includes CO_2 equivalent VOC and CO emissions

Table 2.63 Upstream Emissions from Uranium Conversion, Fabrication and Waste Storage, g/g U-235

	VOC	CO	CH_4	N_2O	CO_2	CO_2*	GHG
Natural Gas	0.261	0.476	5.543	0.008	212.449	214.011	343.790
Electricity	0.317	2.028	4.839	1.610	3050.420	3054.594	3642.348
Total	**0.58**	**2.50**	**10.38**	**1.62**	**3,262.87**	**3,268.605**	**3,986.14**

* Includes CO_2 equivalent VOC and CO emissions

*Table 2.64 Total Emissions from Uranium Conversion, Fabrication and Waste Storage, g/g U-*35

	VOC	CO	CH_4	N_2O	CO_2	CO_2*	GHG
Natural Gas	1.128	7.869	12.911	0.044	2,496.929	2,512.811	2,822.761
Electricity	0.317	2.028	4.839	1.610	3,050.420	3,054.594	3,642.348
Total	**1.44**	**9.9**	**17.75**	**1.65**	**5,547.35**	**5,567.405**	**6,465.11**

* Includes CO_2 equivalent VOC and CO emissions

2.45 Enriched Uranium and Uranium Fuel Transport

Enriched Uranium and Uranium Fuel Transport Energy Use

This portion of the pathway calculates transport of enriched uranium to fabrication and uranium fuel to the reactor. Both assume 100% truck transport.

Transport Energy Btu/ton = Miles * Energy Intensity (Btu/ton-mile) * (1 + WTT of diesel)

The values for this equation are presented in Table 2.65.

Table 2.65 Enriched Uranium and Uranium Fuel Transport Energy

Parameter	Value	Reference
Enriched Ore Transport		
Truck miles	920	GREET Default
Truck Energy Intensity, Btu/ton-mile	1,028	GREET calculated value
WTT energy of diesel fuel, Btu/Btu	0.177	GREET calculated value
Transport Energy, Btu/ton	1,112,839	GREET calculated value
Weight conversion factor	1.18%	GREET Default
Transport Energy, Btu/g U-235	104	GREET calculated value
Uranium Fuel Transport		
Truck miles	500	GREET Default
Truck Energy Intensity, Btu/ton-mile	1,028	GREET calculated value
WTT energy of diesel fuel, Btu/Btu	0.177	GREET calculated value
Transport Energy, Btu/ton	604,804	GREET calculated value
Weight conversion to U-235	0.83%	GREET Default
Transport Energy, Btu/g U-235	80	GREET calculated value
Total Fuel Transport, Btu/g U-235	**184**	GREET calculated value

Enriched Uranium and Uranium Fuel Transport GHG Emissions

The emissions associated with truck transport of fuel are calculated as follows:

$$\text{Emissions g/ton} = (A + B) * C * D / 10^6$$

where the parameters are described in Table 2.66. Resulting emissions in g/ton ore are converted utilizing the conversion factor indicated in Table 2.65. Table 2.67 provides enriched uranium and uranium fuel transport emissions on a per g U-235 basis.

Table 2.66 Values of Properties Used to Calculate Ore Transport Emissions

Parameter	Source
A = diesel truck emission factor, g/mmBtu	AB1007 value
B = WTT diesel emissions g/mmBtu	GREET calculation
C = truck transport energy intensity, Btu/ton-mile	GREET calculation
D = transport miles	GREET default

Table 2.67 Total GHG Emissions Uranium Ore Transport to Enrichment Facility, g/g U-235

GHG	(g/g U-235)	Formula to convert to CO_2e	gCO_2e/g U-235
Enriched Uranium Transport			
CO_2	7.967	7.967*1	7.967
CH_4	0.009	0.009*23	0.206
N_2O	0.000	0.000*296	0.075
CO	0.016	0.016*0.43*(44/12)	0.025
VOC	0.005	0.005*0.85*(44/12)	0.015
CO_2*			8.006
Total Enriched Uranium Transport GHG emissions			8.287
Uranium Fuel Transport			
CO_2	6.15	6.150*1	6.150
CH_4	0.007	0.007*23	0.159
N_2O	0.000	0.000*296	0.058
CO	0.012	0.012*0.43*(44/12)	0.019
VOC	0.004	0.004*0.85*(44/12)	0.011
CO_2*			6.181
Total Uranium Fuel Transport GHG emissions			6.398
Total Enriched and Uranium Fuel Transport GHG			**14.69**

* Includes CO_2 equivalent VOC and CO emissions

APPENDIX C

INPUT VALUES FOR ELECTRICITY PATHWAY

California Average Electricity Mix

Parameters	Units	Values	Note
GHG Equivalent			
CO_2		1	
CH_4		23	
N_2O		296	
VOC		3.1	
CO		1.6	
Power Plants			
Equipment Shares, Emission Factors, and Efficiency			
Residual Oil fired Power Plant - Boiler		100%	Efficiency 34.8%
CO_2 Emission Factor	gCO_2/mmBtu	85,048	
Natural Gas fired Power Plant			Ave Efficiency of Natural Gas Plant 38.9%
Boiler		20%	Efficiency 34.8%
CO_2 Emission Factor	gCO_2/mmBtu	58,198	
Simple Cycle Turbine		36%	Efficiency 31.8%
CO_2 Emission Factor	gCO_2/mmBtu	58,179	
Combined Cycle Turbine		44%	Efficiency 51.8%
CO_2 Emission Factor	gCO_2/mmBtu	58,171	
Coal fired Power Plant - Boiler		100%	Efficiency 34.1%
CO_2 Emission Factor	gCO_2/mmBtu	137,356	
Biomass fired Power Plant - Boiler		100%	Efficiency 32.1%
CO_2 Emission Factor	gCO_2/mmBtu	102,224	
Nuclear			Efficiency 100%
Other (Hydro, Wind)			Efficiency 100%
Fuel Shares			
Residual Oil		0.05%	
Natural Gas		43.1%	
Coal		15.4%	
Biomass		1.1%	
Nuclear		14.8%	
Other (Hydro, Wind)		25.5%	
Upstream Fuel Process			
Residual Oil			
Residual Oil Refining			
Residual Oil Transport			
ocean tanker		24%	720 mi, 72 Btu/mile-ton

Parameters	Units	Values	Note
barge		40%	136 mi, 710 Btu/mile-ton
pipeline		60%	240 mi, 253 Btu/mile-ton
rail		5%	40 mi, 513 Btu/mi-ton
Coal			
Coal Mining			
Coal Transport			
barge		10%	33 mi, 403 Btu/mile-ton
rail		90%	396 mi, 370 Btu/mile-ton
Biomass			
Trees Farming			
Farm Chemicals			N_2, P_2O_5, K_2O, Herbicide, Pesticide
Biomass Transport			40 mi, 17 tons load, 25,690 Btu/mi by HDD truck
Nuclear			
Uranium Mining			
Uranium Ore Transport			1,360 mi, 1,028 Btu/mi-ton, 1,645,067 Btu/ton ore
Uranium Enrichment			
Uranium Conversion, Fabrication, Waste Storage			
Enriched Uranium Ore transport			920 mi, 1028 Btu/mi-ton, HHD truck
Uranium Fuel Transport			500 mi, 1028 Btu/mi-ton, HDD truck
Equipment Shares			
Commercial Boiler - Diesel		25%	
CO_2 Emission Factor	gCO_2/mmBtu	78,167	
Stationary Reciprocating Eng. - Diesel		50%	
CO_2 Emission Factor	gCO_2/mmBtu	77,349	
Turbine - Diesel		25%	
CO_2 Emission Factor	gCO_2/mmBtu	78,179	
Stationary Reciprocating Eng. - NG		50%	
CO_2 Emission Factor	gCO_2/mmBtu	56,551	
Small Industrial Boiler - NG		50%	
CO_2 Emission Factor	gCO_2/mmBtu	58,176	
Industrial Boiler - Coal		100%	
CO_2 Emission Factor	gCO_2/mmBtu	137,383	
Small Industrial Boiler - Biomass			
CO_2 Emission Factor	gCO_2/mmBtu	102,224	
Transmission and Distribution Loss			
Feed Loss in Transmission		8.10%	
Fuels Properties			

Fuels Specifications	LHV (Btu/gal)	Density (g/gal)	
Crude	129,670	3,205	
Residual Oil	140,353	3,752	
Conventional Diesel	128,450	3,167	
Conventional Gasoline	116,090	2,819	
CaRFG	111,289	2,828	
CARBOB	113,300	2,767	
Natural Gas	83,868	2,651	As Liquid
Ethanol	76,330	2,988	
Still Gas	128,590		
Conversion Factors			
For nuclear power plants	MWh/g of U-235	6.926	Light Water Reactor (LWR) Power Plant
	MWh/g of U-235	8.704	High-Temperature, Gas-Cooled Reactor (HTGR) Power Plant
Energy Btu to Kilowatt hour	Btu/K Wh	3,412	
Uranium Yellow Cake to U-235		0.29%	